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Original article

Three-dimensional kinematics of the equine interphalangeal joints: articular impact of asymmetric bearing

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Abstract – The objective of this study was to assess the effects of asymmetric placement of the foot on the three-dimensional motions of the interphalangeal joints. Four isolated forelimbs were used. Trihedrons, made of three axes fitted with reflective markers, were screwed into each phalanx. They allowed to establish a local frame associated with each bone and thus to define the spatial orientation of the phalanges. The limbs were then placed under a power press, and subjected to compression with gradually increasing force (from 500 to 6 000 N). The procedure was performed in neutral position and with the lateral or medial part of the foot raised by a 12° wedge. Flexion, collateromotion (passive abduction/adduction) and axial rotation of the interphalangeal joints were measured using a cardan angle decomposition according to the principle of the "Joint Coordinate System" described by Grood and Suntay. Raising the lateral or medial part of the hoof induced collateromotion (about 5.6° ± 0.8) and axial rotation (about 6.5° ± 0.5) of the distal interphalangeal joint. The proximal interphalangeal joint underwent axial rotation (about 4.7° ± 0.5 at 6 000 N) and slight collateromotion. Both interphalangeal joints underwent collateromotion in the direction of the raised part of the foot (i.e., narrowing of the articular space on the side of the wedge), whereas axial rotation occurred in the direction opposite to the raised part of the foot. These results confirm the functional importance of interphalangeal joint movements outside the sagittal plane. In particular they demonstrate the involvement of the proximal interphalangeal joint in the digital balance. These data are helpful for the identification of biomechanical factors that may predispose to interphalangeal joint injury. Also the data may be of use for the rational decision making with respect to exercise management and corrective shoeing of the lame horse.

horse / biomechanics / joint coordinate system / interphalangeal joint / imbalance

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Résumé – Étude cinématique tridimensionnelle des articulations interphalangiennes chez le cheval: **influence de l'appui asymétrique du pied.** L'objectif de cette étude était de déterminer les effets de l'appui asymétrique du pied sur le comportement tridimensionnel des articulations interphalangiennes. Quatre membres isolés ont été utilisés. Des systèmes de suivi cinématique, pourvus de 3 axes portant des marqueurs réfléchissants ont été vissés dans chaque phalange. Ces systèmes permettaient de déterminer, pour chaque segment osseux, un repère local définissant l'orientation du segment. Les membres ainsi équipés étaient placés sous une machine de compression et soumis à des cycles de mise en charge de 500 à 6 000 N, en modifiant l'orientation du sabot par l'apposition d'une cale de 12^o sous le quartier latéral ou médial. Les angles de flexion, collatéromotion (abduction/adduction passive) et rotation axiale des articulations interphalangiennes ont été calculés selon le principe du « Système d'Axes Articulaires » énoncé par Grood et Suntay. Les modifications de l'appui transversal du pied ont provoqué un mouvement de collatéromotion (5,6^o ± 0,8) et de rotation axiale (6,5^o ± 0,5) au sein de l'articulation interphalangienne distale. L'articulation interphalangienne proximale a subi un faible mouvement de collatéromotion et une rotation axiale d'environ 4,7^o ± 0,5. Pour les deux articulations interphalangiennes, le mouvement de collatéromotion intervenait toujours en direction du quartier surélevé (i.e., rétrécissement de l'interligne articulaire du côté de la cale) alors que le mouvement de rotation axiale s'effectuait dans le sens opposé au côté de la cale. Ces résultats sont une indication quantitative de l'importance fonctionnelle des mouvements extra-sagittaux des articulations interphalangiennes. Ils démontrent, en particulier, l'implication de l'articulation interphalangienne proximale dans l'équilibre du segment digital. Ces données sont utiles pour confirmer ou pour suggérer objectivement des facteurs biomécaniques intervenant dans l'étio-pathogénie des lésions interphalangiennes. En corollaire, cette démarche permet de rationaliser certaines indications thérapeutiques (gestion de l'exercice et maréchalerie orthopédique) chez le cheval boiteux.

cheval / biomécanique / système d'axes articulaires / articulation interphalangienne / appui asymétrique

1. INTRODUCTION

Lateromedial foot imbalance is believed to be a common cause of, or a predisposing factor for locomotor injuries in the horse [2, 5, 9, 21, 22]. It has been demonstrated that the elevation of one area of the equine foot results in an increased load in that region of the foot, which leads to the conclusion that a horse is unable to compensate for an acute foot imbalance by redistributing the load under the foot [22]. However, the biomechanical effects of such imbalance on three-dimensional (3-D) motions of the joints remain poorly documented [17, 20].

Taking into account the shapes of the bones and the congruence of the joints, the equine interphalangeal joints are designed to undergo primarily flexion/extension. However, asymmetric bearing, associated with misalignment between the hoof and the limb, is supposed to induce joint motions outside the sagittal plane (such as passive abduction/adduction and axial rotation) [5, 8, 10]. Many authors [2, 3, 8, 19, 20] have pointed out the functional importance of these movements, as they are considered to counteract the effect of asymmetric bearing when the horse is walking on irregular surfaces or moving around a curve. These movements are suspected by clinicians to be a cause of articular pain and joint damage [10, 12, 15]. Experimental evidence is therefore needed to clearly demonstrate the biomechanical relationship between asymmetric bearing and 3-D behaviour of the interphalangeal joints.

The occurrence of motions outside the sagittal plane in the interphalangeal joints has been documented using intra-articular injection of a coloured solution and subsequent analysis of variations in the articular contact areas [8]. It has been shown qualitatively that asymmetric bearing induces a combination of passive abduction/adduction in the frontal plane and axial rotation in the transversal plane [11]. Radiographic assessment, based on measurement of several angles, has also been proposed [4, 5] in order to quantify the rotation of the proximal phalanx relative to the distal one. This method is, however, restricted to a measurement of combined movements between the proximal and distal interphalangeal joints. The distinction between axial rotation and abduction/adduction remains complex, as discrimination between these movements using a geometrical projection on a single plane is difficult.

To date, no quantitative information is available on the effects of asymmetric bearing on the 3-D motions of the interphalangeal joints. According to the principle of the Joint Coordinate System [14], a method based on a cardan angle decomposition has been developed to describe joint motion as ordered rotations about three axes for each digital joint [7]. With this method, the effects of asymmetric bearing on the metacarpophalangeal joint (MPJ) have been quantified on isolated forelimbs [6]. The objective of the present study was to assess, in vitro, the effects of asymmetric bearing on articular motion in both interphalangeal joints.

2. MATERIALS AND METHODS

2.1. Experimental procedure

2.1.1. Horse limbs

Four left forelimbs were collected from adult horses (518 ± 42 kg) that had been subjected to euthanasia for reasons unrelated to the musculoskeletal system. The humeri were cut above the elbow joint, immediately proximal to the humeral insertion of the *extensor carpi radialis* muscle, thus preserving the insertions of the digital flexor muscles. The hooves were uniformly trimmed by the same farrier.

2.1.2. Definition of bone-linked local coordinate systems

One trihedron per bony segment defined the three axes of a coordinate system [7]. Four reflective markers covered with scotchlite (Scotchlite 7610 – 3-M, Cergy-Pontoise, France) were fixed on the axes. The trihedrons were screwed into the lateral side of each phalanx (through the hoof wall for the distal phalanx). They were oriented so as the Z-axis coincide with the proximodistal axis of each bone, the Y-axis with the lateromedial axis and the X-axis with the dorsopalmar axis (Fig. 1).

2.1.3. Recording procedure

The 3-D coordinates of the markers of the trihedrons were recorded by three 8 mm 25 Hz video cameras (FX 700 – Sony, Tokyo, Japan) that had been placed in front of a power press (MTS 10/MH – Adamel Lhomargy, Ivry-sur-Seine, France). Two of them were mounted on video tripods. The third camera was positioned at a height of 2.5 m, in order to record a proximodistal view of the limb. The recording field was calibrated using a geometric structure fitted with markers of known 3-D coordinates. The latter allowed spatial reconstruction in a field of 552 mm diagonal length.

2.1.4. Experimental conditions

The isolated limbs were placed under the power press in a mid-stance phase position. All limbs were pre-loaded with a load of 500 N. From this initial position, the load was increased up to 6 000 N by the regular displacement of the piston of the power press (500 mm/min).

Two asymmetric tests were performed with the hoof laterally or medially raised by a 12^{o} wedge, and a reference test (called neutral test) was performed without any wedge. Each of these 3 experimental conditions was repeated 3 times in a Latin square design.

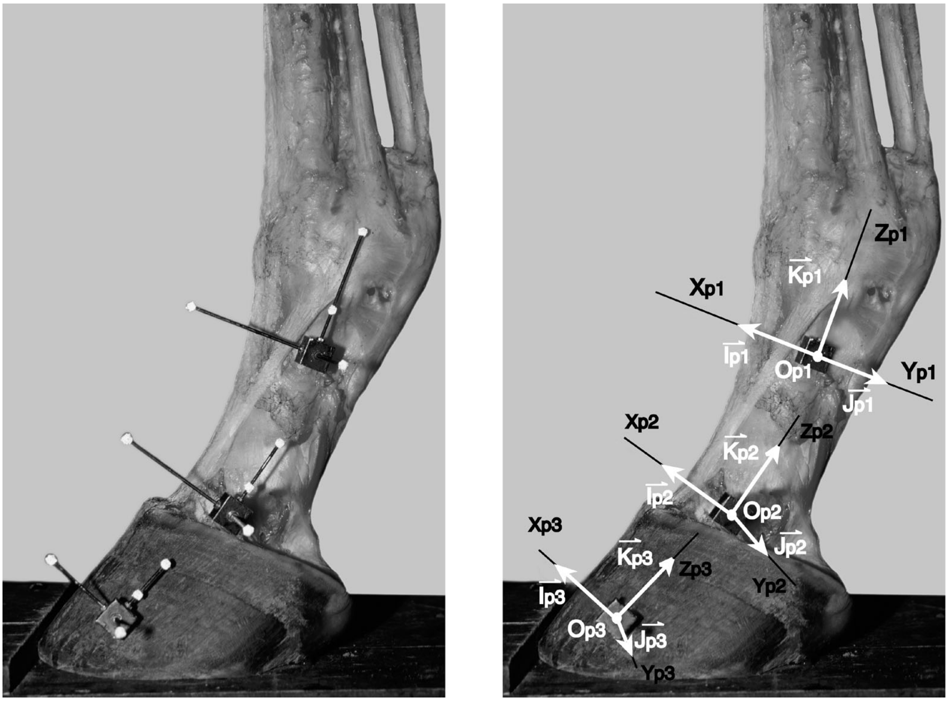

Figure 1. Representation of the kinematic devices (trihedrons) screwed into the lateral aspect of the phalanges and their relation with the axes of the bones. Each trihedron defines a local coordinate system associated with the bone.

2.1.5. Three-dimensional transformation

The films, once digitized, were analysed using the Equine Kinematic Analysis System [18]. The bi-dimensional coordinates of the markers were measured on each film and their 3-D coordinates were reconstructed using Direct Linear Transformation [1].

2.2. Angle computing

2.2.1. Principle of the modelling

The 3-D coordinates of the markers defined the spatial orientation of the trihedrons. The principle of the Joint Coordinate System [14] was applied to the proximal (PIPJ) and distal (DIPJ) interphalangeal joints. Thus, a cardan (Euler) angle decomposition was performed to achieve three ordered rotations: flexion/extension, collateromotion and axial rotation for each interphalangeal joint (Fig. 2), as described by Degueurce et al. [7].

The 3 angles were calculated using Microsoft Excel software (Microsoft France, Les Ulis, France). The palmar joint angle was used to represent the flexion/extension angle of the joints; so that a flexion resulted in a decrease of this palmar angle. The concept of collateromotion, established by Denoix [11] was used to describe the passive abduction/adduction movements. A lateromotion (or passive abduction) is a rotation in the frontal plane of the distal segment in a lateral direction. Mediomotion,

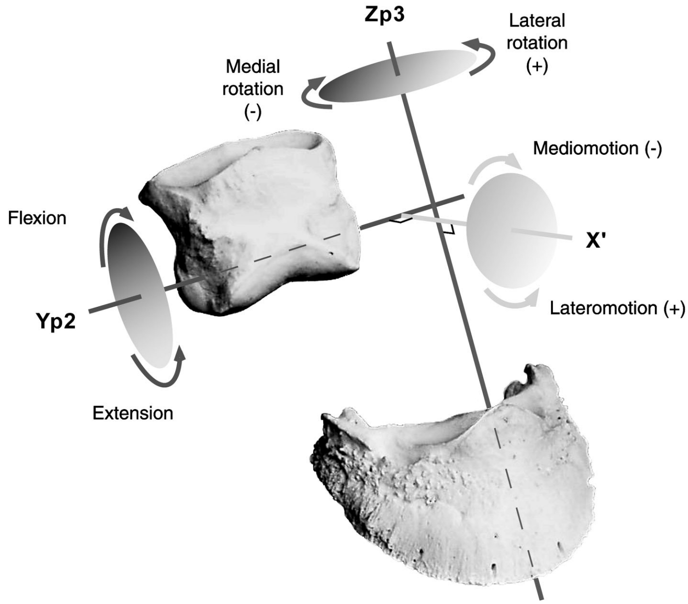

Figure 2. Definition of the Joint Coordinate System (JCS) applied to the left distal interphalangeal joint. Rotations of the distal phalanx relative to the middle phalanx occur around the three axes of this JCS.

on the other hand, describes the opposite phenomenon (passive adduction). In the present Joint Coordinate System convention, a change of the collateromotion angle in positive direction (+) indicates a lateromotion and vice-versa (Fig. 2). Lastly, a change of the axial rotation angle in positive direction (+) corresponds to a lateral rotation of the distal segment relative to the proximal one, and vice-versa (Fig. 2).

2.2.2. Statistical analysis

The absolute values of the joint angles at the beginning (500 N) and at the end (6 000 N) of each test were obtained from which the angular amplitudes were calculated. The relative values of the angles under each condition at 500 N and 6 000 N were obtained by subtraction from the neutral condition considered as reference. The statistical significance ($p < 0.05$) of this difference was tested using an ANOVA (GLM procedure of SAS, SAS Institute, North Carolina, USA), and the difference between final and initial values for a same experimental condition was tested using a paired Student test ($p < 0.05$).

The means and standard deviations of the absolute and relative angles were calculated. The mean of the standard deviations of a parameter for the 4 limbs provided the intra-individual variability (IAV) of this parameter. The standard deviation of the 4 means gave the inter-individual variability (IEV).

3. RESULTS

3.1. Flexion/extension

During neutral loading (with the hoof in a flat position), the PIPJ underwent a small flexion and the DIPJ a more pronounced flexion. The amplitude of these movements was respectively 8.1° ± 4.6 and 28.0° ± 4.2.

The addition of either a medial or lateral wedge induced a slight decrease in the magnitude of flexion of both interphalangeal joints (Tab. I).

3.2. Collateromotion

Without a wedge, no significant collateromotion was observed neither in the PIPJ nor in the DIPJ during limb loading.

In both interphalangeal joints, the addition of a lateral or medial wedge induced a collateromotion in the direction of the raised part of the foot (Tab. II). Thus, a lateral wedge induced a lateromotion and a medial wedge, a mediomotion. The magnitude of this movement varied for each joint.

At 500 N, the PIPJ underwent a small (although significant) collateromotion in the direction of the wedge (Tab. II). At 6 000 N, no statistically significant difference with the neutral test was observed when the foot was raised by a lateral wedge, whereas a small but significant difference was observed with a medial wedge.

Contrary to the PIPJ, the DIPJ underwent a large collateromotion at 500 N (Tab. II). This phenomenon decreased with

Table I. Mean, standard deviation (sd), inter-individual variability (IEV) and intra-individual variability (IAV) of the *amplitude of flexion* (°) from 500 N to 6 000 N for the proximal (PIPJ) and distal (DIPJ) interphalangeal joints.

Joint	Condition	Mean (sd)	IEV	IAV
PIPJ	Neutral	8.1° (4.6)	5.1	0.3
	Lateral wedge	7.4° (4.8)*	5.3	0.3
	Medial wedge	6.0° (4.8)*	6.0	0.3
DIPJ	Neutral	28.0° (4.2)	4.6	0.5
	Lateral wedge	26.8° (4.3)*	4.7	0.7
	Medial wedge	27.5° (5.1)*	5.6	0.6

*Significantly different from the neutral test ($p < 0.05$).

Table II. Mean, standard deviation (sd), inter-individual variability (IEV) and intra-individual variability (IAV) of the *relative angle of collateromotion* of the proximal (PIPJ) and distal (DIPJ) interphalangeal joints. In the present Joint Coordinate System convention, a positive value indicates a lateromotion and a negative value a mediomotion.

Joint	Condition	Load	Mean (sd)	IEV	IAV
PIPJ	Lateral wedge	500 N	+ 1.4° (0.3)*	0.2	0.2
		6 000 N	0.0° (0.6)≠	0.6	0.2
	Medial wedge	500 N	– 1.3° (0.4)*	0.3	0.3
		6 000 N	– 1.1° (0.7)*	0.8	0.2
DIPJ	Lateral wedge	500 N	+ 5.6° (0.8)*	0.8	0.4
		6 000 N	+ 0.5° (1.5)≠	1.4	0.5
	Medial wedge	500 N	– 4.2° (1.5)*	1.5	0.5
		6 000 N	– 0.5° (0.8)≠	0.8	0.2

*Significantly different from the neutral test ($p < 0.05$).
≠Significantly different from the initial load ($p < 0.05$).

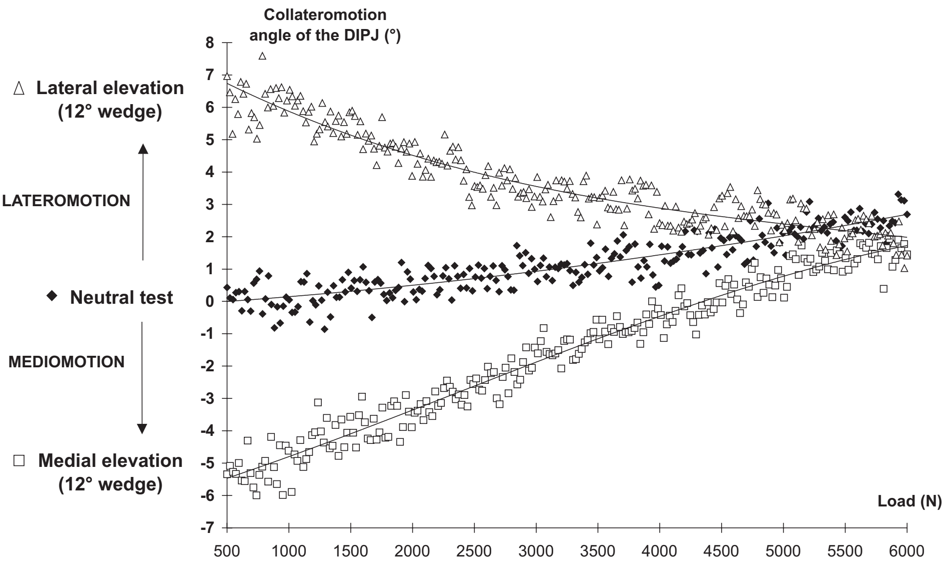

Figure 3. Influence of elevation of the lateral and medial side of the hoof (12° wedge) on collateromotion of the distal interphalangeal joint (DIPJ), during loading of the limb (limb 4).

the loading of the limb and became non significant at 6 000 N (Tab. II and Fig. 3).

3.3. Axial rotation

During neutral loading, the final angle of axial rotation was not significantly different from the initial one, neither in the PIPJ nor in the DIPJ.

Conversely, in both interphalangeal joints, asymmetric loading induced a rotation of the distal segment in the direction opposite to the raised part of the foot. Thus, a lateral wedge induced a medial rotation and a medial wedge a lateral rotation (Tab. III). Axial rotation of the PIPJ was substantial at 500 N and increased with the load (Tab. III and Fig. 4). There was a large axial rotation of the DIPJ, even with low loads (Tab. III). This rotation remained approximately the same during limb loading (Fig. 5).

4. DISCUSSION

The objective of this study was to quantify the effects of asymmetric bearing on the three angles of rotation of the interphalangeal joints, and to assess 3-D motions of these joints outside the sagittal plane.

4.1. Methodological background and modelling of the joints

The principle of the geometric modelling of the joints has been described by Degueurce et al. [7]. The use of the Joint Coordinate System [14], according to the recommendations of the *International Society of Biomechanics* [23], allowed to quantify, separately and continuously, the collateromotion and axial rotation angles. The model chosen was deliberately limited to 3 degrees of freedom in rotation. Although translations exist in the digital joints

Table III. Mean, standard deviation (sd), inter-individual variability (IEV) and intra-individual variability (IAV) of the *relative angle of axial rotation* of the proximal (PIPJ) and distal (DIPJ) interphalangeal joints. In the present Joint Coordinate System convention, a positive value indicates a lateral rotation and a negative value a medial rotation.

Joint	Condition	Load	Mean(sd)	IEV	IAV
PIPJ	Lateral wedge	500 N	–3.1° (0.7)*	0.7	0.2
		6 000 N	–4.7° (0.5)*#	0.5	0.2
	Medial wedge	500 N	+2.8° (0.9)*	1.0	0.3
		6 000 N	+4.8° (0.4)*#	0.3	0.3
DIPJ	Lateral wedge	500 N	–6.5° (0.5)*	0.4	0.4
		6 000 N	–6.7° (1.1)*	1.1	0.3
	Medial wedge	500 N	+6.2° (1.3)*	1.2	0.7
		6 000 N	+6.2° (0.9)*	0.9	0.4

*Significantly different from the neutral test ($p < 0.05$).
#Signficantly different from the initial load ($p < 0.05$).

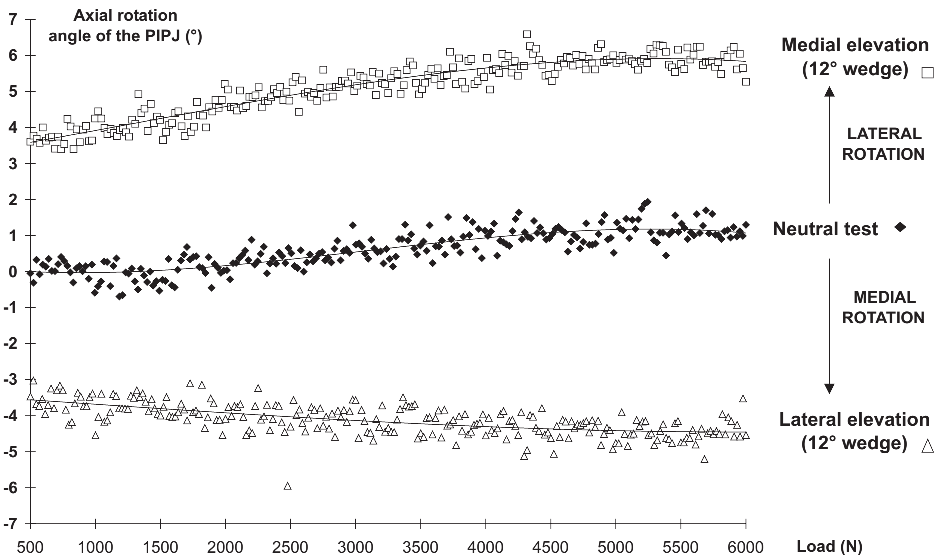

Figure 4. Influence of elevation of the lateral and medial side of the hoof (12° wedge) on axial rotation of the proximal interphalangeal joint (PIPJ), during loading of the limb (limb 4).

[8], the accurate assessment of these movements was not within the scope of this study.

The precision of the method was established at less than 0.3° for the angles [7]. However, as the exact orientation of each trihedron in relation to the anatomical axes of the bones was difficult, the study aimed at the comparison of different conditions (medial or lateral elevations of the foot vs. flat neutral position), rather than at the generation of absolute values. The low inter-individual variability of the relative results (Tabs. II and III), and the highly reproductive

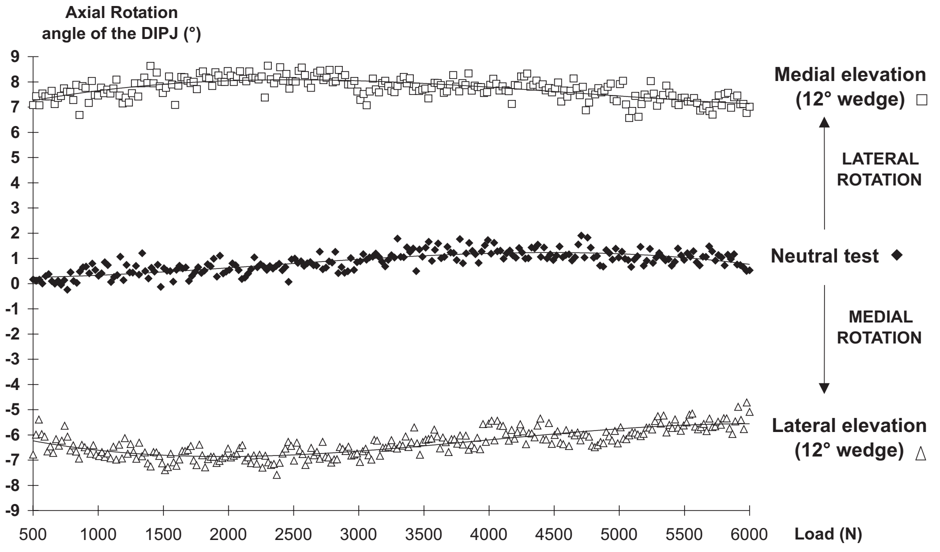

Figure 5. Influence of elevation of the lateral and medial side of the hoof (12° wedge) on axial rotation of the distal interphalangeal joint (DIPJ), during loading of the limb (limb 4).

pattern in which the joints respond to loading with and without wedge justified such comparative use of the data.

4.2. In vitro experimental set-up versus in vivo physiological conditions

This study was conducted in vitro, on isolated forelimbs, placed in a position that simulates the mid-stance phase of the stride.

The load that was applied increased from 500 N to 6 000 N. The latter value has been shown to correspond to the ground reaction force of horses at trot [16]. In fact, the 6 000 N load resulted in a slightly higher extension of the metacarpophalangeal joint than induced by a slow trot (3 $m \cdot s^{-1}$) [6]. Muscle activities and dynamic effects of the displacement of the limbs and of the whole body were not taken into account. It is therefore acknowledged that, although the absolute amount of loading was representative of the trot, the rate of loading and orientation of the limb did not mimic the situation in the living animal.

In the experimental set-up, transverse alterations of the foot orientation were produced by a 12° wedge, raising successively the lateral and medial parts of the hoof, in order to reproduce asymmetric bearings. This 12° wedge is obviously higher than would be used in the clinical setting to produce small changes in latero-medial hoof balance. However, it is consistent with the physiological conditions for a horse trotting on a circle on a hard surface, taking into account the displacement of the centre of gravity and the orientation of the limb. In fact, this 12° elevation remains moderate and is considerably less than is seen during quick turns in sport horses.

4.3. Behaviour of the interphalangeal joints under neutral conditions

Without a wedge, the interphalangeal joints undergo a pure flexion. In contrast with the metacarpophalangeal joint, which undergoes a lateral rotation during extension [6, 13], neither axial rotation nor collateromotion is associated with the flexion of the interphalangeal joints when the hoof is in a flat, neutral position.

4.4. Alterations induced by asymmetric bearing

In both interphalangeal joints, asymmetric bearing induced a collateromotion (narrowing of the articular space) in the direction of the raised part of the foot and an axial rotation in the opposite direction.

These results confirm the previous semi-quantitative observations that were obtained by the analysis of the variations in the articular contact areas [8], and from radiographic studies [5].

This combination of collateromotion and axial rotation has also been observed in the metacarpophalangeal joint [6]. In the same experimental set-up, at 6 000 N, a 12° lateral wedge induced lateromotion (2.1° ± 0.4) and medial rotation (–0.9° ± 0.2) of the MPJ. A 12° medial wedge induced the opposite movements.

These data allow to assess the role of each interphalangeal joint in the whole digital complex (metacarpophalangeal and interphalangeal joints), both in terms of functionality and with respect to the occurency of injury.

4.4.1. Functional analysis

This study demonstrates that the PIPJ undergoes substantial movements outside the sagittal plane during asymmetric bearing. Axial rotation of the PIPJ was already evident at 500 N, and increased with the load. It reached more than 4.7° at 6 000 N, which is almost equal or even higher than the amplitude of PIPJ flexion for two of the tested specimens. Besides, this increase in axial rotation was associated with a slight decrease in joint flexion, probably due to the asymmetric position of the joint and the tightening of the soft tissues (capsule and collateral ligaments) surrounding the articular space. This indicates that the PIPJ is fully involved in compensating for asymmetric bearing. At a load of 6 000 N, about 40% of total axial rotation in the whole digital segment is accounted for the PIPJ.

The DIPJ is most influenced by unbalanced loading. At 500 N, the DIPJ underwent more than 4.2° of collateromotion and 6.2° of axial rotation. For low loads, the DIPJ accounts therefore for most movements outside the sagittal plane in the whole digital complex (about respectively 70 and 63% of the total amount of collateromotion and axial rotation of the digital segment at 500 N).

Collateromotion of the DIPJ was large at 500 N, but tended to decrease when the joint flexed. The increase in strain of the deep digital flexor tendon, at the palmar aspect, and of the dorsal digital extensor tendon, dorsally, may contribute to the realignment of the joint during limb loading. This phenomenon is associated with an increase in collateromotion of the MPJ [6], and an increase in axial rotation of the PIPJ. In summary, at low loads the DIPJ accounts for most of the 3-D motions outside the sagittal plane, but, with increasing load the involvement of this joint becomes less whereas the involvement of the PIPJ and MPJ increases.

4.4.2. Relation with injury

The movements which are measured in this study are normal events for the joints. They demonstrate the physiological ability of the interphalangeal joints to compensate for asymmetric bearing. However, when exceeding the joint capacity, these movements probably contribute to damage to joint surfaces and peri-articular ligaments. The relative importance of axial rotation during asymmetrical loading may help to explain why lamenesses due to disorders of the interphalangeal joints are more pronounced during clinical examination when horses are subjected to lunging work on a short circle [12].

Degenerative diseases of the PIPJ are generally supposed to be the result of repeated stress during athletic performance [21]. They indeed occur most frequently in horses used for high speed that make short turns and rapid twisting movements [20]. The present experimental results support previous biomechanical hypotheses [8, 19], and shed light on the functional circumstances that may induce these disorders. If strong asymmetrical placement of the foot (such as stepping in a hole) may induce acute ligament injury, excessive and repeated twisting and tensile forces applied to the collateral ligaments and capsule may lead to a continuous low-grade stress of the joint [21].

A similar pathogenic mechanism may be true for the DIPJ too. Furthermore, contrary to the PIPJ, axial rotation of the DIPJ is associated with a strong collateromotion, opening the articular space and increasing the strain on the collateral ligament on the side opposite to the elevated part of the foot [11].

4.4.3. Consequences for treatment of disorders and prevention

Considering the biomechanical factors and functional circumstances that lead to these potentially damaging movements, it follows that work in short circles on the lame limb, irregular surfaces, and shoes with excessive lateral expansion should be avoided in horses suffering from osteoarthrosis of the proximal or distal interphalangeal joint. As the impact of asymmetric bearing on the DIPJ appears to be substantial, even at low loads, restriction of exercise should even be more stringent in animals suffering from osteoarthrosis of this joint.

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